

# Diode-pumped long-pulse-length Ho:Tm:YLiF<sub>4</sub> laser at 10 Hz

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An optical efficiency of 0.052 under normal mode operation for diode-pumped Ho:Tm:YLiF<sub>4</sub> at a pulse repetition frequency of 10 Hz has been achieved. Laser output energy of 30 mJ in single Q-switched pulses with 600-ns pulse length were obtained for an input energy of 3 J. A diffusion-bonded birefringent laser rod consisting of Ho:Tm-doped and undoped pieces of YLF was utilized for 10-Hz operation.

Diode-pumped 2- $\mu\text{m}$  solid-state lasers have received considerable attention recently for detection of wind velocities as well as for remote sensing of carbon dioxide and water vapor in the atmosphere. High-power Q-switched holmium lasers are also useful as pump sources for optical parametric oscillators for generating tunable mid-infrared radiation for optical remote sensing and/or infrared countermeasure systems. In addition, medical applications for 2.0- $\mu\text{m}$  lasers include arthroscopic surgery, laparoscopic cholecystectomy, and refractive surgery with laser thermal keratoplasty methods.

A Ho:Tm:YLiF<sub>4</sub> (Ho:Tm:YLF) laser, operating normal mode at a pulse repetition frequency of 10 Hz, has achieved a laser output energy of 130 mJ/pulse at an optical conversion efficiency of 0.052. Previously reported pulsed diode-pumped 2- $\mu\text{m}$  lasers either have used Ho:Tm:Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> as the laser material or have been operated at cryogenic temperatures.<sup>1-4</sup> High-efficiency end-pumped Ho:Tm:YLF lasers have been demonstrated, which tend to be either continuous wave or produce modest energies per pulse.<sup>5-8</sup> The laser performance reported in this study was obtained with a water-cooled laser rod and transverse pumping geometry.

We achieved operation of this laser at pulse repetition frequencies up to 10 Hz by using a composite Ho:Tm:YLF laser rod fabricated from three pieces of this birefringent material. We fabricated the laser rod by diffusion bonding two undoped pieces of YLF to a piece of Ho:Tm:YLF, one at each end. Because YLF is a birefringent material, extra precautions were taken during the fabrication and the diffusion-bonding processes to ensure precise alignment of the *c* axes of all the components and thus avoid depolarization. When the diffusion-bonded rod was placed between crossed polarizers, an extinction ratio of 1500:1 was measured with a He-Ne laser. The diffusion-bonding process involves precision polishing, assembly by optical contacting, and heat treatment. Such a diffusion-bonded laser rod with undoped end pieces allows pumping of the full length of the doped YLF piece while avoiding ground-state absorption losses in the unpumped ends of the laser

rod. In two previous studies diffusion bonding of isotropic YAG single crystals was demonstrated.<sup>9,10</sup>

When operated in a Q-switched mode, this laser produces the 600-ns-long pulse lengths required for accurate wind velocity measurements. A 4-m ring resonator was used to yield 600-ns-long pulses. Several approaches, such as relaxation oscillations or Q switching with resonators designed for pulse stretching, can be utilized to generate long pulse lengths.<sup>11</sup> The approach used in our study has the advantages of simplicity and efficiency.

A narrow spectral bandwidth is required so that the smallest Doppler shift of a wind-sensing system is commensurate with the spectral bandwidth of the laser pulse. In turn, the long pulse length results from Fourier-transform limits on the narrow-spectral-bandwidth pulse. Long pulse lengths are required for the narrow, transform-limited bandwidths needed to measure wind velocity to  $\pm 1.0$  m/s.

For our experiments, a 42-mm-long diffusion-bonded laser rod with a 4-mm diameter was utilized. The *a* axis laser rod consists of 20-mm-long Ho:Tm:YLF and two 11-mm-long undoped YLF pieces diffusion bonded at each end of the doped YLF piece. The reflection losses at the bonded interface for YAG composite laser rods were measured by Lee *et al.* to be less than 0.001.<sup>9</sup> Similar reflection losses are also expected for bonded YLF laser rods. The laser rod has 30-min opposing wedged ends that are antireflection coated at 2.06  $\mu\text{m}$ . The concentrations of Ho and Tm were 0.005 and 0.04, respectively, for the doped YLF piece.

The laser pump head design, consisting of two sets of five laser diode arrays (LDA's) placed symmetrically around the perimeter of the laser rod, is shown in Fig. 1. The 4-mm-diameter laser rod at the center of the pump head is encased by a fused-silica glass flow tube with a 5-mm inner diameter and a 7-mm outer diameter, respectively. The laser rod is directly cooled by the flow of water. Because the O-ring seals occur on an unpumped section of the laser rod, minimal thermal stress on the laser rod will occur at the seals. The temperature of the coolant flow was maintained at 16 °C in our experiments.

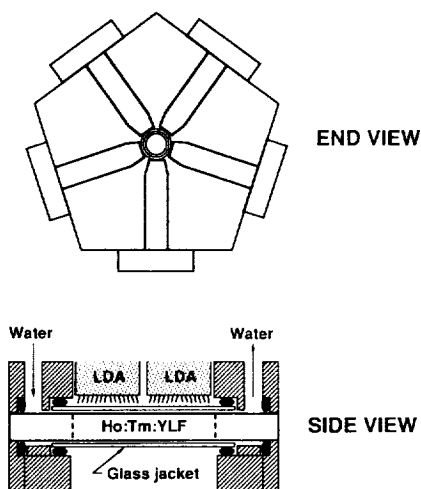


Fig. 1. Design of the water-cooled pump head.

Nominal coolant flow rate around the laser rod was 1 L/min. This flow rate corresponds to laminar flow in our system. In total, 10 diode arrays were used to pump a 20-mm length of Ho:Tm:YLF. The LDA's were six-bar-stack devices with 300-W peak power. The pulse repetition frequency was varied from 1 to 10 Hz, and the current pulse length was 1 ms. We temperature tuned the LDA's by controlling the temperature of the circulating cooling water. A center wavelength of  $0.792 \mu\text{m}$  was selected for optimum absorption of the pump light by the  $a$ -axis Ho:Tm:YLF laser rod.

A maximum optical-to-optical efficiency of 0.052, corresponding to 130 mJ of laser output energy for 2.526-J optical input energy, was achieved with a 0.90-reflecting output coupling mirror. The slope efficiencies and threshold energies were measured in a 50-cm-long standing-wave resonator composed of an 80-cm radius-of-curvature high reflector and various flat output coupling mirrors. Results of these experiments at 10 Hz, with various output mirror reflectivities, are shown in Fig. 2. We did not obtain data at high pump energies for the 0.98- and 0.94-reflecting output mirrors so we could avoid optical damage that is due to high circulating fluences in the resonator. The slope efficiency is 0.144 for the 0.90 output coupling mirror and is 0.134 of the 0.94 output coupling mirror. Laser output wavelength was centered at  $2.065 \mu\text{m}$  for various output coupling mirrors. These results obtained at a pulse repetition frequency of 10 Hz are comparable with the results previously reported for 1-Hz operation of Ho:Tm:YLF.<sup>12</sup> The significant increase in pulse repetition frequency is attributed to pumping all the doped length of gain medium as well as to better extraction of heat from the laser rod. Higher efficiencies or higher pulse repetition frequency operation can be obtained by decreasing the temperature of coolant flow around the laser rod. The observed laser output was multitransverse mode for this resonator.

The efficiency of the diode-pumped Ho:Tm:YLF laser is limited by the available pump energy. Flash-lamp-pumped Ho:Tm:Cr:YAG lasers can have a comparable efficiency because they can be pumped

by a factor of 2.0 over optical transparency. In addition, Cr is an efficient absorber of the flashlamp radiation, and the quantum efficiency can be high. In the diode-pumped Ho:Tm:YLF case, pumping is limited to a factor of 1.3 over optical transparency. Thus, even though the quantum efficiency can also be high for the diode-pumped case, the overall efficiency is comparable with that of flash-lamp-pumped Ho:Tm:Cr:YAG. Higher efficiencies should also be possible by closer coupling of the laser diode arrays to the laser rod.

We have obtained the requisite 600-ns-long  $Q$ -switched pulses by using a 4-m ring resonator in a figure-eight configuration. This ring resonator consists of two flat high reflectors, a 4.5-m radius-of-curvature high reflector, and a 0.82-reflecting output coupler. An acousto-optic  $Q$  switch made of water-free fused silica having Brewster faces was used for  $Q$ -switched operation. In our experiments the acousto-optic  $Q$  switch was adjusted for a particular pump energy to produce unidirectional operation of this ring resonator. The  $Q$ -switching approach used in a ring resonator permits long photon lifetimes, yielding longer pulse lengths, and, because spatial hole burning is eliminated, narrow-frequency laser outputs are possible. We measured laser output energies and pulse lengths of  $Q$ -switched pulses by varying the input optical pump energies for various pulse repetition frequencies. Pulse lengths were measured with a fast-response gold-doped germanium detector.

We have achieved maximum laser output energies of 30 mJ in a single  $Q$ -switched TEM<sub>00</sub>-mode pulse with a 590-ns pulse length for an input energy of 3 J, corresponding to a 0.01 optical-to-optical efficiency. Results of this study for a pulse repetition frequency of 10 Hz are shown in Fig. 3. We achieved unidirectional operation by adjusting the  $Q$  switch around Bragg angle, as reported in earlier studies by Clarkson *et al.*<sup>13</sup> For the results shown in Fig. 3, the acousto-optic  $Q$  switch was adjusted to produce unidirectional operation with a laser output energy of 30 mJ. At energies below 15 mJ the ring laser operated in both directions.

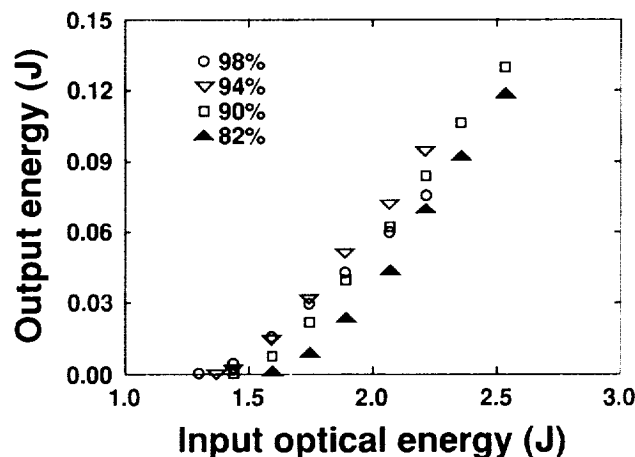


Fig. 2. Slope efficiencies and threshold energies for a 50-cm-long resonator at a pulse repetition frequency of 10 Hz and a coolant flow temperature of  $16^\circ\text{C}$ .

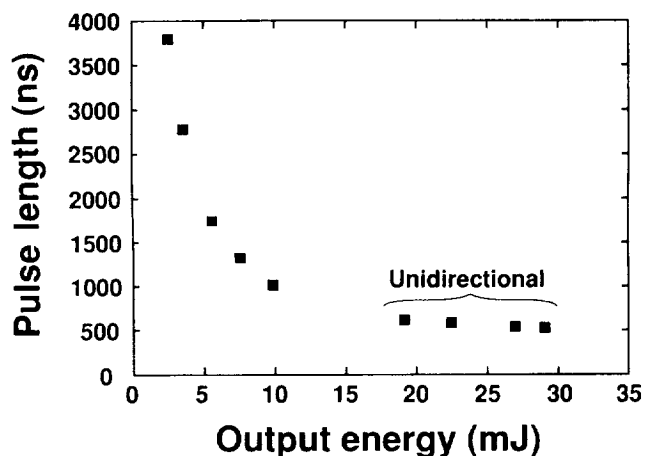


Fig. 3. Pulse lengths and output energies of single Q-switched pulses for a 4-m ring resonator at a pulse repetition frequency of 10 Hz and a coolant flow temperature of 16 °C.

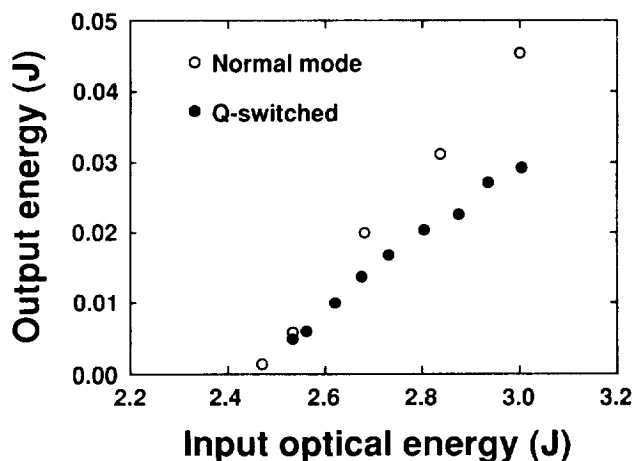


Fig. 4. Slope efficiencies and threshold energies for a 4-m ring resonator at a pulse repetition frequency of 10 Hz and a coolant flow temperature of 16 °C.

60% of the normal mode energy was extracted into single Q-switched pulses for this ring resonator. Q-switched and normal mode performances with the same resonator conditions are shown in Fig. 4. The beam quality of our laser output is 1.4 times diffraction limited, and the variation of the beam quality as a function of input average power is less than 0.1. This observation is in agreement with results obtained for Nd:YLiF<sub>4</sub> by Murray.<sup>14</sup>

The laser output wavelength was centered at 2.052  $\mu\text{m}$ , with a FWHM of 220 pm, which is the resolution limit of our detection system. By inserting an étalon into the resonator we were able to vary the output laser wavelength from 2.052 to 2.066  $\mu\text{m}$ . Such a laser system would be useful for differential absorption lidar measurements. Experiments are in progress on injection seeding of this laser to achieve narrow optical bandwidths needed for velocity resolution.

For the water-cooled laser system no parasitic lasing was observed, as expected, even at the highest

pump energies available. Parasitic lasing can occur on total internal reflection modes of the laser rod. Lasing on these modes reduces the laser output energies and thus the efficiency of the laser system. Parasitic lasing will make it impossible to increase the stored energy, which limits efficiency of the laser system. Once parasitic lasing starts, all further pump energy is converted into parasitic lasing modes and therefore is not available in the single Q-switched pulses.

In conclusion, we have shown an optical-to-optical efficiency of 0.052 for normal mode operation of a diode-pumped Ho:Tm:YLF laser at a pulse repetition frequency of 10 Hz. Maximum output energy of 30 mJ was obtained in single Q-switched pulses with 590-ns pulse lengths corresponding to an optical-to-optical efficiency of 0.01. We achieved operation of this laser system at 10 Hz by using a diffusion-bonded birefringent laser rod consisting of doped and undoped pieces of YLF.

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